

FINAL REPORT

PROJECT NUMBER 47986CI DECENTRALIZED ALGORITHMS FOR LOCALLY INTERACTING MOBILE ROBOTS

Magnus Egerstedt
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332, USA
magnus@ece.gatech.edu
<http://www.ece.gatech.edu/~magnus>

1. FOREWORD

This three year project has focused on the development of decentralized algorithms for teams of mobile robots that are to operate using local interaction rules in such a way that desired, global objectives are achieved. In particular, these robots are constrained through limitations on their sensing and communications capabilities. As such, the main problem under consideration is how to develop systematic communications and controls protocols in order to ensure that the team achieves some desired, global performance objective based solely on local interaction rules.

The way this problem has been addressed is by finding the correct level of abstraction where one can effectively describe the interaction rules without having to take the actual communication channels and non-linear vehicle dynamics into account, yet ensuring that the obtained results are robust enough to support such real-world constraints. In fact, by identifying individual robots with nodes in a graph, and by encoding the existence of communication links between robots through edges in the graph, a high-level description of the robot team is obtained. In this manner, the low-level, continuous behaviors of the individual robots can be abstracted away, with the result of allowing coordination and control issues to be addressed at the graph-level. What this means is that we can study formation control problems as problems involving selecting, achieving, and maintaining the appropriate graph structure.

This way of letting graph-based team models represent the high-level interactions between robots has allowed us to address a number of questions, including:

1. How should the local interactions be structured in order to ensure that the graph stays connected, i.e. so that the team does not split up into two or more separate teams?
2. If the robots are heterogeneous, how should the interactions be structured in order to take maximal advantage of the different capabilities of the different robots?
3. What formations (graphs) are to be preferred in what circumstances?
4. How can the graph-based abstraction be used to provide decision support for operators controlling teams of unmanned vehicles?

This final report collects the main results obtained as part of this research effort and contains the following illustrations:

Figure 1. Decentralized Algorithms with Guaranteed Global Properties

Figure 2. Autonomous Formation Selection

Figure 3. Control of Heterogeneous Mobile Networks

Figure 4. Graph-Theoretic Methods for Multi-Agent Networks

2. STATEMENT OF THE PROBLEM STUDUED

Although this project has focused on providing a general, fundamental theory for how to coordinate multi-robot systems, three key research thrusts and problem statements have been identified as the most important.

2.1. From Local Rules to Global Properties

Local interaction rules are typically useful for ensuring local properties, such as maintaining desired inter-robot distances. However, global properties must also be guaranteed. For example, the team of robots should not break up into smaller sub-teams without any way of returning to their original, larger team. This type of question, regarding how to ensure that global properties can be ensured using local interactions only, is arguably the main scientific challenge in multi-agent robotics today.

2.2. Selection of Useful Formations

Given a desired target formation, we have developed decentralized algorithms for achieving and maintaining the formation. However, different formations are more appropriate in different situations due to factors such as spatial constraints, required information and communication flows, and desired response times. Unfortunately, no complete systematic study or methodology has, as of yet, been proposed for actually solving the formation selection problem in the first place.

2.3. One-to-many Control of Unmanned Vehicles

Assuming that the robot team is executing a particular mission in a coordinated and autonomous fashion, there is the potential for improving the performance if an operator temporarily takes control of individual robots. For this, questions relating to the controllability of the graph-abstractions become important in the sense that only certain interaction topologies allow for effective control of the overall team. A thorough understanding of this issue still remains elusive.

3. SUMMARY OF THE MOST IMPORTANT RESULTS

To be able to endow a large number of relatively simple robots with local interaction rules in order to guarantee desired, global objectives would have a significant impact on the robotics community in general. Such capabilities would mean that large, expensive, mission critical robots could be replaced by teams of flexible, cheap, and versatile robots with the built-in redundancy as an added bonus. Moreover, to be able to answer questions about what the robots should do (controls) and what they need to talk about

(communications) in a unified manner is of importance not only to the robotics community. In networked control problems, or when designing distributed software, similar questions arise. Moreover, the type of robotics applications for which decentralized coordination schemes are relevant are potentially very important in their own rights, including autonomous planetary missions, mine sweeping and securing of other dangerous areas, search and rescue applications, including disaster sites, and autonomous military missions.

The most important results obtained as part of this research effort are as follows:

3.1. Connectivity Preserving Formation Control

A number of decentralized algorithms have been previously proposed by other researcher that achieves desired team objectives if certain global formation properties can be obtained. In particular, the entire body of previous work has either assumed global rather than local interaction rules, or that the formation stays connected at all times, or that it suffices to ensure connectedness only at distinct times. The reason why connectedness is such a key property is that a formation that has lost connectedness has effectively no chance of returning to a full formation again. Hence connectedness is a very important property and we have shown, though this project, that for a large number of the existing algorithms, the connectedness assumptions are false, i.e. they can not be guaranteed. Instead, we have shown how to add nonlinear weights to the tension-potentials in-between interacting robots to ensure that no interactions are lost, and hence preserving connectivity. This methodology has been used successfully on the *rendezvous problem* (how drive all robots to one point?) and the *formation control problem* (how make the robots achieve and maintain a given geometric formation?)

An example of applying the developed control strategy is shown in Figure 1.

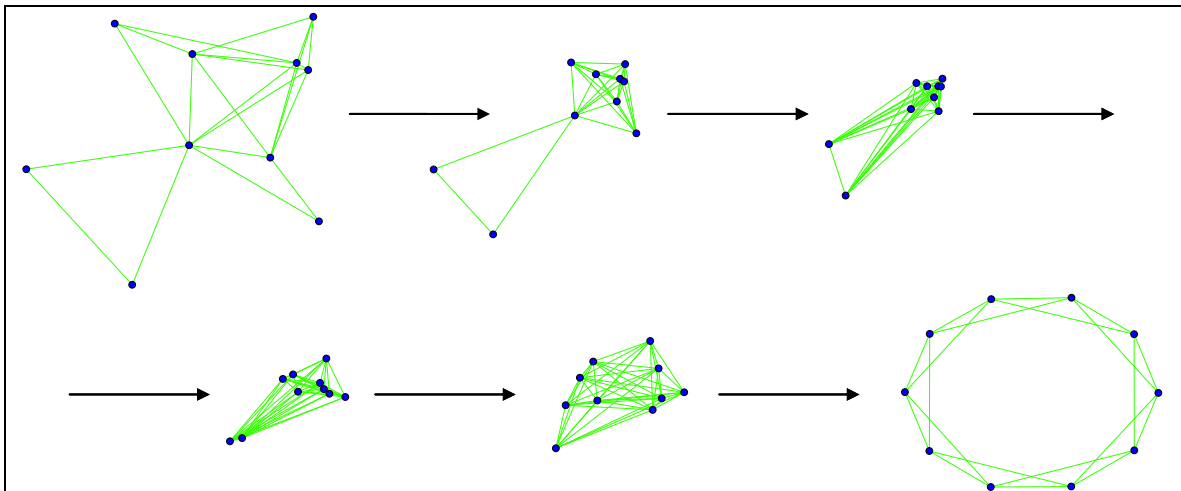


Figure 1. Decentralized Algorithms with Guaranteed Global Properties: The progression shows the evolution of a team of mobile robots that reaches the desired target formation while ensuring that the network remains connected at all times.

3.2. Decentralized Formation Selection

As robots move around in an unknown and unstructured environment, different formations are to be preferred in different situations. For example, a moderately spread formation might be preferable in a search-and-rescue application, while a more tight formation is more suitable when negotiating dense obstacles. We have developed a theory for achieving decentralized formation selection. The basic idea is to endow each agent with a parameterized set of possible formations. Based on how the individual agents perceive the environment, they will prefer different formations in this set, and a decentralized “consensus” algorithm has been developed for ensuring that the agents are able to resolve their differences with respect to what formation they want to use. Novel techniques have moreover been developed for trading off formation-relevant information pertaining to the usefulness for the entire team, to information of use to the individual agents.

An example of letting the agents select the appropriate formations in reaction to environmental changes is shown in Figure 2.

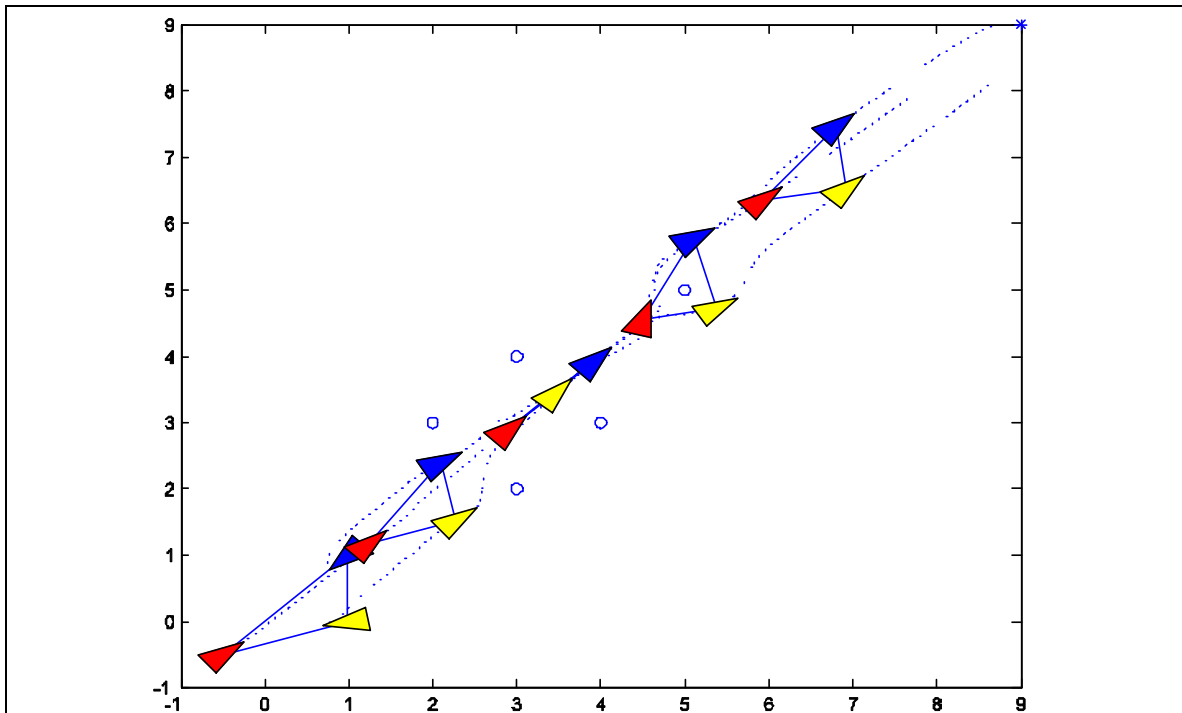


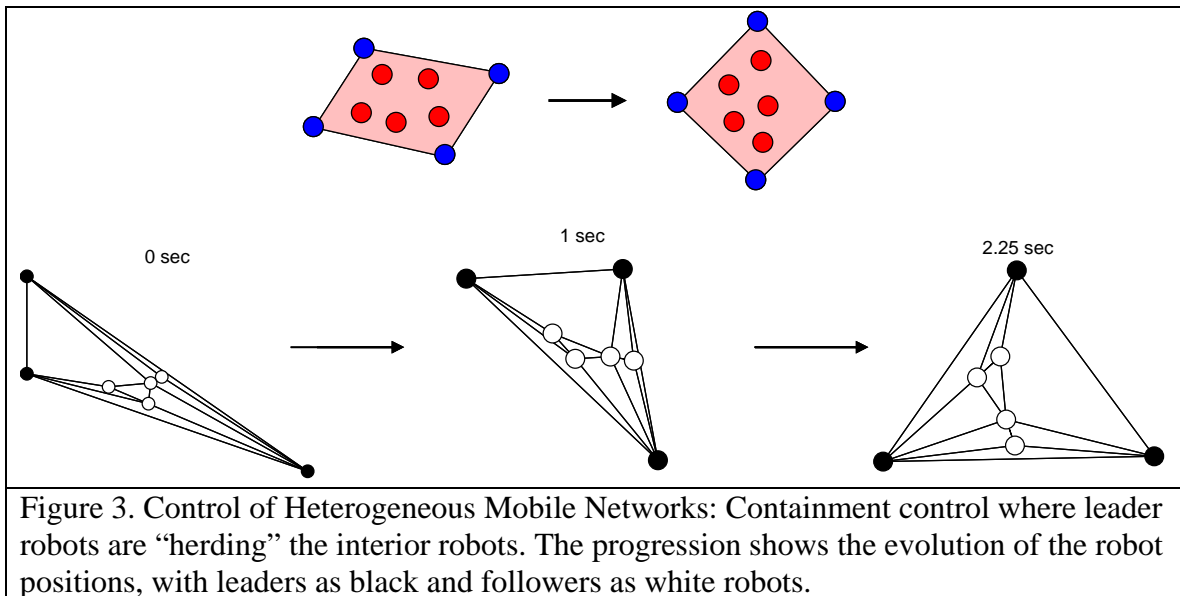
Figure 2. Autonomous Formation Selection: The three robots start out in a triangular formation but as obstacles (circles in the plot) are encountered in the environment, they switch to a line-formation. Once the obstacles have been negotiated, the triangular formation is selected again. Depicted are the positions of the three robots.

3.3. Heterogeneous (Leader-Based and Remote Controlled) Networks

It is not always the case that the robot team is homogeneous, i.e. that the individual robots have exactly the same capabilities. For instance, they may differ in terms of sensory resources, onboard communication and computation capabilities, and in terms of

the motions that the different robots can execute. We have investigated how such heterogeneities can be taken advantage of in so-called containment controls problems. The main idea is to let the large majority of robots be fairly simple in that they can only execute simple control commands based solely on short-range information. These robots can for instance be transporting hazardous materials or other loads that must be prevented from leaving a predefined area. In order to ensure this, more agile leader-robots are “herding” the robots, and we have developed algorithms for driving collections of robots between configurations in an orderly manner by letting the leader-robots manipulate the boundary of the formation. Along a similar line of thought, a study has been initiated of how to design interaction topologies that allow for effective control of large teams of unmanned vehicles. In particular, sufficient conditions for this to be possible have been produced through a study of symmetries in multi-agent networks.

The idea of using leader-based control of heterogeneous networks is illustrated in figure 3.



4. CONCLUSIONS

To go from local rules to guaranteed global behaviors is arguably the key challenge facing multi-agent control and communications tasks today. Since August 2005 when this project was initiated, we have been able to address this problem along three different vantage points, namely:

1. Decentralized algorithms for formation control have been developed that ensure that a desired, global formation is achieved and maintained at the same time as the network connectivity is guaranteed.
2. Novel, decentralized algorithms have been developed for selecting the appropriate formations in given situations. This allows us to deploy teams of locally interacting mobile robots that are flexible in that they adapt to environmental changes as the mission evolves.

3. Leader-based and human-operated control strategies have been studied that allows for more agile leader-robots to indirectly dictate the motion of the remaining robots, which thus enables heterogeneous robot teams to capitalize on the different capabilities of the different robots.

An another noteworthy outcome of this research is the textbook that is slated to appear in 2009 on “Graph-Theoretic Methods for Multi-Agent Networks”, by M. Mesbahi and M. Egerstedt, Princeton University Press, as shown in Figure 4.

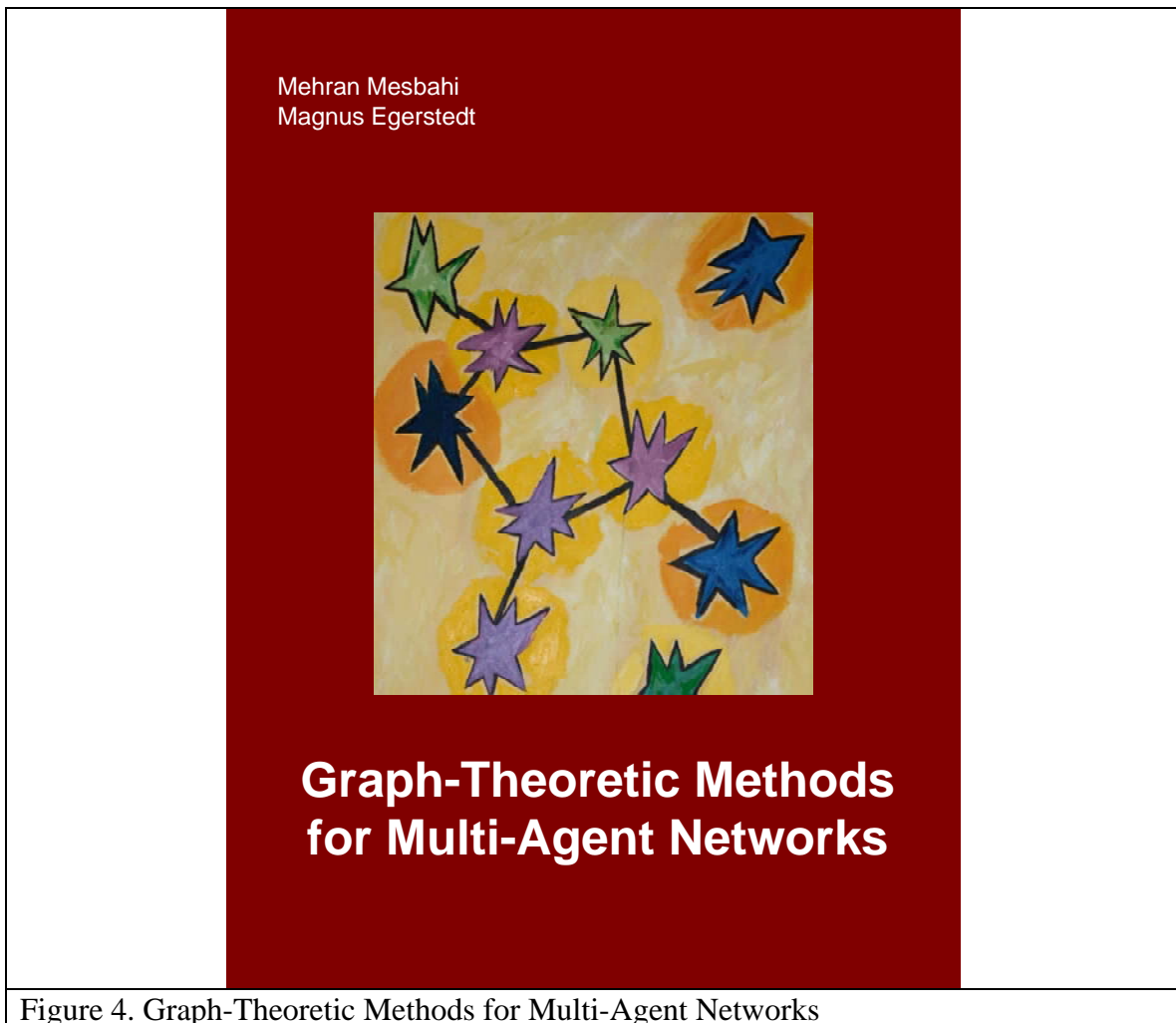


Figure 4. Graph-Theoretic Methods for Multi-Agent Networks